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RESEARCH MEMORANDUM

EFFECT OF PARTICLE SIZE AND STABILIZING ADDITIVES ON THE COMBUSTION PROPERTIES OF MAGNESIUM SLURRY

By Albert M. Lord and Vernida E. Evans

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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EFFECT OF PARTICLE SIZE AND STABILIZING ADDITIVES ON THE COMBUSTION PROPERTIES OF MAGNESIUM SLURRY

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SUMMARY

An experimental investigation was conducted with a $1\frac{7}{8}$-inch-diameter burner to determine the effects of particle size and of stabilizing additives on the combustion performance of magnesium-hydrocarbon slurry fuels. The fuels tested were MIL-F-5624-A grades JP-3 and JP-4 and slurries of magnesium in JP-3 fuel.

A slurry composed of $4\frac{1}{2}$-micron magnesium particles had a leaner mixture limit at which a flame could be maintained and a maximum blow-out velocity much higher than a slurry composed of 20-micron particles.

The combustion efficiency of the metal in the $4\frac{1}{2}$-micron slurry was consistently higher than in the 20-micron slurry in spite of its being burned at a much higher burner-inlet velocity.

The slurries stabilized with petrolatum had combustion efficiencies and blow-out velocities comparable to those of the gel-stabilized slurries.

INTRODUCTION

The use of metal-hydrocarbon slurries as fuels in jet-engine propulsion systems has been the subject of analytical and experimental investigations at the NACA Lewis laboratory. As a result of these investigations substantial improvements in air specific impulse have been realized in an experimental afterburner by the addition of magnesium powder to conventional hydrocarbon fuel (reference 1). In reference 2 it was shown that in a tail-pipe burner operating with water injection a magnesium slurry could be burned at a much higher water-air ratio than was possible with JP-3 fuel.

The higher air specific impulse of the metal-hydrocarbon slurry over the hydrocarbon alone is due mainly to the higher heat of combustion per pound of air of the slurry when compared with hydrocarbon at the same equivalence ratio. References 3 to 5 report the results of analytical investigations in which the equations of chemical equilibrium were solved for the composition and temperature of the combustion products of octene-1 and mixtures of aluminum, magnesium, and boron in octene-1 when burned in air. Values of theoretical air specific impulse at stoichiometric fuel-air ratio for octene and the slurries were computed and shown to be higher for each of the slurries than for the hydrocarbon.

Reference 6 reports the results of an experimental investigation to 2735
determine how the metal and hydrocarbon separately contribute to the over-all combustion of magnesium and boron slurries. The combustion efficiency (ratio of energy released to energy available by complete combustion) of the magnesium powder component of slurries was unaffected by oxygen depletion as fuel-air ratio was increased above stoichiometric, whereas the combustion efficiency of the hydrocarbon portion of the mixture declined rapidly.

Magnesium powder of smaller particle size has recently become available; and petrolatum, a viscous hydrocarbon, has been used as a stabilizing additive. The finer powder has less tendency to separate out of a slurry suspension, but a stabilizing additive still is a practical necessity in slurry fuel systems. Petrolatum-stabilized slurries offer some advantages over the gel-stabilized slurries previously investigated because of ease of preparation and reproducibility of viscosity, and because they do not break down (decrease in viscosity) with age as gels do.

The object of the present investigation was to determine the effect of particle size and stabilizing additive on the combustion properties of magnesium slurries in a $1\frac{7}{8}$-inch-diameter burner. The blow-out velocities (burner-inlet velocities at which flame failure occurred) were determined for magnesium slurries in JP-3 fuel having average magnesium particle sizes of 20, 12, and $4\frac{1}{2}$ microns. Both gel- and petrolatum-stabilized slurries were investigated. The blow-out velocities of two hydrocarbon fuels, MIL-F-5624-A, grades JP-3 and JP-4, were determined for comparison with slurry fuel performance.

The combustion efficiencies of the metal and hydrocarbon components were determined for both the $4\frac{1}{2}$- and 20-micron magnesium slurries stabilized with gel and with petrolatum. Combustion efficiency was determined by sampling and analyzing the gaseous and solid combustion products.

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SYMBOLS

The following symbols are used in this report:

CO_2/C	molecular weight ratio of CO_2 to C when C burns to CO_2
CO_2/CO	molecular weight ratio of CO_2 to CO when CO burns to CO_2
f	fuel-air weight ratio determined by flow rate measurements of air and fuel
f'	fuel-air weight ratio determined by sampling and analyzing combustion products
H/C	hydrogen-carbon weight ratio
h_{CO}	heat of combustion of carbon to carbon monoxide, Btu/lb CO
h_{CO_2}	heat of combustion of carbon to carbon dioxide, Btu/lb CO_2
h_{H_2O}	heat of combustion of hydrogen to water (lower value), Btu/lb H_2O
W_C	weight of solid carbon in combustion sample[a]
W_{CO}	weight of carbon monoxide in combustion sample[a]
W_{CO_2}	weight of carbon dioxide in combustion sample[a]
W'_{CO_2}	weight of carbon dioxide formed by catalytic combustion of gaseous hydrocarbon residues in combustion sample[a]
W_{HC}/W_a	hydrocarbon-air weight ratio
W_{H_2O}	weight of water in combustion sample[a]
W'_{H_2O}	weight of water formed by catalytic combustion of gaseous hydrocarbon residues on combustion sample[a]
W'_M	weight of uncombined metal in combustion sample[a]
W_M/W_a	metal-air weight ratio
W_{mo_x}/W_m	molecular weight ratio of metal oxide to metal

[a]The combustion sample was the total of gas and solids drawn through the sampling probe.

W_S weight of solids in combustion sample[a]

η_{HC} combustion efficiency of hydrocarbon

η_M combustion efficiency of metal

φ equivalence ratio

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APPARATUS AND PROCEDURE

Combustor and Operating Procedure

The slurry burner and exhaust sampling apparatus are shown in figure 1. The burner consisted of a $1\frac{7}{8}$-inch-inside-diameter tube 20 inches long. A tube liner with an outside diameter of $1\frac{5}{8}$ inches, a thickness of 1/16 inch, and length of 2 inches was mounted at the inlet and provided a small primary zone through which the atomized fuel was introduced. Secondary air was introduced as an annular stream along the burner wall. The secondary-air inlet was about 1 inch from the burner entrance.

The slurry was atomized and injected into the burner with a conventional paint spray gun of the type that pressurizes the fluid. The spray nozzle was sealed to the burner entrance. The flow rate of the fuel was set by a valve on the spray gun and was measured by weighing the spray gun before and after a timed flow interval. The flow of the air entering the burner was regulated with a throttling valve and was measured with a rotameter. The burner was ignited by opening the seal between the gun and the burner and holding an acetylene torch to the opening.

Sampling apparatus and procedure. - The sampling-probe assembly consited of a 1/4-inch-outside-diameter copper tube incased in a water jacket. The outer wall of the jacket was covered with asbestos insulation. The 1/4-inch copper tube was connected to a solids-sampling tube, which was packed with glass wool to collect the metal oxide, unburned metal, and carbon particles. The assembly was mounted so that it could be swung into the path of the flame, as indicated in figure 1. A rubber stopper sealed the opening of the probe. It was held in place by atmospheric pressure when the sampling apparatus was evacuated. As the probe moved toward the center of the burner exit, the stopper was brushed off by the edge of the burner, thus permitting the exhaust gases and solids to be drawn in.

[a]The combustion sample was the total of gas and solids drawn through the sampling probe.

A 30-gallon vacuum tank was evacuated by the vacuum pump to about 1 inch of mercury absolute. The valve between pump and tank was closed while a sample was taken. The pressure in the tank was measured with a mercury manometer. A coil of copper tubing packed in powdered dry ice served to remove the moisture from the gases entering the vacuum tank.

The exhaust-gas sample was collected in the gas-sampling tube as follows: Both valves on the gas sampling tube were open when the sampling began, the downstream valve was closed after about 20 seconds of burning operation, and then the upstream valve was closed after the pressure in the sampling tube had risen to atmospheric.

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<u>Test procedure.</u> - For the combustion-efficiency tests the air flow was adjusted to give an inlet-air velocity of 22 feet per second for the 20-micron slurries and 80 feet per second for the $4\frac{1}{2}$-micron slurries. The velocity was increased for the latter fuels because the finer particles burned with high efficiency over the entire range of equivalence ratio, and it was necessary to create more severe burner conditions to distinguish the regions of lowered efficiency.

For the investigation of blow-out velocities, the velocity of the air flow was first set below the blow-out limit of the fuel mixture and gradually increased until flame failure occurred. This velocity was taken as the blow-out limit.

<u>Method of analysis.</u> - The quantity of the combustion sample referred to in subsequent definitions includes all combustion products drawn through the sampling probe. It is computed from the composition of the gases in the sample tube, the pressure rise in the vacuum tank, and the weight of the sample of solids.

By analysis of the solid and gas samples, the weights of the following constituents of the combustion sample were determined: N_2, CO_2, CO, H_2O, total solids, carbon, uncombined metal, and CO_2 and H_2O, formed by catalytic combustion of unburned residues in the gas sample.

The analysis of the gaseous products was determined with an Orsat apparatus equipped with a catalytic heater for the combustion of hydrocarbon residues. The nitrides in the solid samples were found to be less than 0.1 percent and were neglected. No carbonates were found in the solids.

The amount of uncombined magnesium in the solid samples was determined by introducing an acid solution into the solids-sampling tube and measuring the volume of hydrogen evolved. The solids-sampling tube was weighed before the sampling, washed with distilled water after the acid treatment, dried, and weighed again. The gain in weight was taken as solid carbon.

<u>Combustion efficiency</u>. - The combustion efficiencies reported herein are not based upon chemical equilibrium of the products of combustion inasmuch as data are not available for the various species involved. Instead, 100-percent combustion efficiency assumes that the components oxidize as follows:

$$H_2 \text{ to } H_2O$$

$$C \text{ to } CO_2$$ 2735

$$Mg \text{ to } MgO$$

The combustion efficiency of the metal is defined as

$$\eta_M = \frac{\left[W_S - (W'_M + W_C)\right]}{\left[W_S - (W'_M + W_C)\right] + W'_M \dfrac{W_{mo_x}}{W_m}}$$

The combustion efficiency of the hydrocarbon is defined as

$$\eta_{HC} = \frac{W_{CO_2}h_{CO_2} + W_{CO}h_{CO} + W_{H_2O}h_{H_2O}}{\left(W_{CO_2} + W_{CO}\left(\dfrac{CO_2}{CO}\right) + W'_{CO_2}\right) h_{CO_2} + (W_{H_2O} + W'_{H_2O})\ h_{H_2O} + W_C\left(\dfrac{CO_2}{C}\right)h_{CO_2}}$$

Combustion efficiencies so defined are in substantial agreement with the conventional combustion efficiency at and below an equivalence ratio of unity. At equivalence ratios higher than unity, the combustion efficiencies do not account for deficiency of oxygen, as they are based only on the utilization of fuel.

DESCRIPTION OF FUELS

The following fuels were used in this investigation.

Fuel number	Average magnesium particle size μ	Magnesium (percent)	MIL-F-5624-A fuel		Additive		Viscosity[a] (centi-poises)
			Grade	Percent	Type	Percent	
I	---	0	JP-3	100		0	2
II	---	0	JP-4	100		0	2
III	---	0	JP-4	99.2	Gel	0.8	10,000
IV	---	0	JP-4	60	Petrolatum	40	840
V	20	50	JP-3	49.5	Gel	0.5	980
VI	20	50	JP-3	29	Petrolatum	21	4700
VII	12	50	JP-3	29	Petrolatum	21	3670
VIII	$4\frac{1}{2}$	50	JP-3	34	Petrolatum	16	4970
IX	$4\frac{1}{2}$	50	JP-3	49.4	Gel	0.6	3960

[a]Viscosity measured with Brookfield Syncro-lectric viscometer, no. 3 spindle, 12 rpm at 30-34° C.

Properties of the JP-3 and JP-4 fuels used are listed in the following tables:

Distillation Range

Fuel evaporated (percent)	Temperature (°F)	
	Grade JP-3	Grade JP-4
Initial b.p.	106	140
10	177	222
50	299	300
90	417	427
Final b.p.	479	488

Properties	Grade JP-3	Grade JP-4
Reid vapor pressure, lb/sq in.	6.2	2.5
Sp. gr. at 60° API	55.8	52.8
Sp. gr. at 60° F/60° F	0.755	0.768
H/C	0.171	0.169
Heat of combustion, Btu/lb	18,725	18,675
Aniline point, °F	135.5	134.6
Bromine number	1.0	1.2

The magnesium powders were found by analysis to contain spherical particles only and to contain about 98 percent free magnesium with impurities of less than 2 percent as magnesium oxide. The particle size designations used herein to describe the powders was determined with a Fisher Sub Sieve Sizer. This instrument employs the air permeability method for measuring the average particle size of a powder. It is based upon the fact that a current of air flows more readily through a bed of coarse powder than through an otherwise equal bed of fine powder. Sieve analysis of the 20-micron magnesium was 98 percent through a 325 mesh screen. 2735

A batch of the 20-micron magnesium powder was placed in an air elutriator (an instrument used to separate fine powders into graded size increments), where 78 percent by weight of the coarser particles were removed to give the 12-micron powder used in this investigation.

Photomicrographs of the particle-size distribution of the magnesium powders are shown in figure 2.

The gelling agent used in the slurries was aluminum di(2-ethyl) hexoate. Aluminum di(2-ethyl)hexoate melts and decomposes at 300° C. The gelling agent served to thicken and to stabilize the slurry (reduced the tendency for the powder to settle out of the liquid).

The petrolatum stabilizer additive used in the slurries conformed to the following manufacturing specification:

Melting point (Saybolt), °F	150-160
Penetration (A.S.T.M.)	140
Viscosity (Saybolt), sec at 210° F	90-100

By analysis, it was found that the hydrogen-carbon ratio (H/C) was 0.160, and the lower heat of combustion 18,400 Btu per pound.

RESULTS AND DISCUSSIONS

Evaluation of sampling method. - The precision of the sampling apparatus and analytical procedure is indicated in figures 3 to 6. The deviations of the data points from the ideal represent the sum of the experimental error. Some of the immediately apparent sources of the error are discussed in this section.

A comparison of the fuel-air ratio determined by inlet air and fuel flow f and the fuel-air ratio determined by exhaust products analysis f' is shown in figures 3 and 4; the dashed line in each figure represents the ideal. It is seen that the f' points are on the average less than the corresponding f. The deposition of some of the unburned fuel and solid combustion products on the inside of the burner walls and probe before they reached the sampling tube (fig. 1) would make a difference in the values of f and the corresponding f' in the direction indicated in the figures.

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The possibility of f' varying across the burner-exit cross section was checked by taking combustion-product samples of fuel VIII at one-half and three-fourths of the radial distance from the center line to the burner wall. The results are shown in figure 4. It is seen that there was uniform distribution of the combustion products across the burner exit.

The $4\frac{1}{2}$-micron slurries gave f/f' ratios that averaged much closer to the ideal than the 20-micron slurries.

The metal-hydrocarbon ratio as found by combustion-products analysis is shown in the plots of metal-air ratio W_M/W_a against hydrocarbon-air ratio W_{HC}/W_a in figures 5 and 6. In figure 6 the results of a radial survey of metal-hydrocarbon ratio for fuel VIII showed that the metal-hydrocarbon ratio was uniform across the burner exit. The dashed line in each figure represents the metal-hydrocarbon weight ratio used in making the slurry.

With few exceptions, the metal-hydrocarbon ratio as found by analysis was lower than that used to make the slurry. The quantity of solid products in the exhaust stream was reduced by the amount of oxide which adhered to the burner walls and then flaked off in agglomerations that were too large to enter the sampling probe. Oxide particles as large as 1/2 inch were observed in the burner-exhaust stream.

The $4\frac{1}{2}$-micron slurries gave metal-hydrocarbon ratios by products analysis that averaged much closer to those used in making the fuels than the 20-micron slurries.

Blow-out velocity. - A comparison of the blow-out velocities of JP-3, JP-4, and JP-4 with gel and petrolatum additives is shown in figure 7. Each data point was found by fixing the fuel-flow rate and then increasing the air-flow rate until flame failure occurred. When the fuel-flow rates were set to give mixture values slightly lower than the lean limits (minimum fuel-air ratio for supporting combustion) shown in the figure, the blow-out velocity occurred below the lower limit of the scale of the air rotameter (shown by dashed line). It was concluded that the curves drop sharply at their lean end although the data points do not always clearly define this trend.

The JP-3 and JP-4 fuels had no appreciable difference in their blow-out velocities while the additives raised the lean limit at which burning could be maintained. The gel additive raised the lean limit more than the petrolatum. It is observed that the large increase in viscosity resulting from the additives affected the blow-out velocity only in the lean region.

In figure 8 the blow-out velocities of 20-micron and 12-micron 50 percent magnesium slurries stabilized with petrolatum are compared with the blow-out velocities for the JP-4 plus petrolatum mixture. The 20-micron magnesium powder served only to reduce the lean limit at which the flame of the JP-4 and petrolatum mixture could be maintained; the smaller-particle-size slurry (12 μ) further reduced the lean limit. 2735

The blow-out velocities of the 20-micron and $4\frac{1}{2}$-micron magnesium slurries are shown in figure 9. Arrowheads on the data points indicate that the maximum air-flow rate of the apparatus was reached with the $4\frac{1}{2}$-micron slurries without the flame blowing out. The $4\frac{1}{2}$-micron slurries had a leaner limit at which a flame could be maintained and a maximum blow-out velocity much higher than the 20-micron slurries. No appreciable difference in the blow-out velocity of the 20-micron magnesium slurries with gel and with petrolatum was observed. With $4\frac{1}{2}$-micron particle size, the petrolatum-stabilized slurry burned to slightly leaner fuel-air ratios than did the gel-stabilized slurry.

Combustion efficiency. - The effect of equivalence ratio φ on the combustion efficiency of the metal η_M and the hydrocarbon η_{HC} in the 20- and $4\frac{1}{2}$-micron slurries is shown in figures 10 and 11. The 20-micron slurries were burned at a burner-inlet velocity of approximately 22 feet per second and the $4\frac{1}{2}$-micron slurries at approximately 80 feet per second. The combustion efficiencies of the hydrocarbon in each of the four slurries were not appreciably different (fig. 10).

It is seen (fig. 11) that the combustion efficiency of the magnesium component was unaffected by oxygen depletion as the fuel-air ratio was increased above stoichiometric up to the limits of the data. The rapid decline of the combustion efficiency of the hydrocarbon component in the rich region indicates that the magnesium burns first and the hydrocarbon reaction yields increasing amounts of incomplete combustion products as the fuel-air ratio is increased. This same behavior was previously noticed in reference 6 where the combustion properties of similar magnesium slurries were studied.

The combustion efficiency of the metal in the 20-micron slurry which was stabilized with petrolatum was higher than in the 20-micron slurry stabilized with gel (fig. 11). In the $4\frac{1}{2}$-micron slurries, the kind of additive made no appreciable difference in the combustion efficiency of the metal. The $4\frac{1}{2}$-micron magnesium had a consistently higher efficiency than the 20-micron powder in spite of its being burned at a much higher burner-inlet velocity. The samples of fuel VIII taken at one-half and three-fourths radial positions showed the combustion efficiency of metal and hydrocarbon to be uniform across the burner exit.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effects of particle size and stabilizing additives on the combustion properties of magnesium slurries:

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1. The $4\frac{1}{2}$-micron magnesium slurries burned with a higher combustion efficiency than the 20-micron magnesium slurries even though the $4\frac{1}{2}$-micron slurries were burned at a much higher burner-inlet velocity. The $4\frac{1}{2}$-micron slurries could be burned to a leaner mixture limit and to much higher combustor velocities than the slurries composed of the larger magnesium particles.

2. The combustion efficiency of the hydrocarbon component of the magnesium slurries was not appreciably affected by the type of additive and the particle size of magnesium.

3. The slurries stabilized with petrolatum had a combustion efficiency and blow-out velocity comparable with those stabilized with gel.

4. The blow-out velocity of hydrocarbon fuel thickened with an additive so that its viscosity increased from 2 to 10,000 centipoises was affected only in the lean region.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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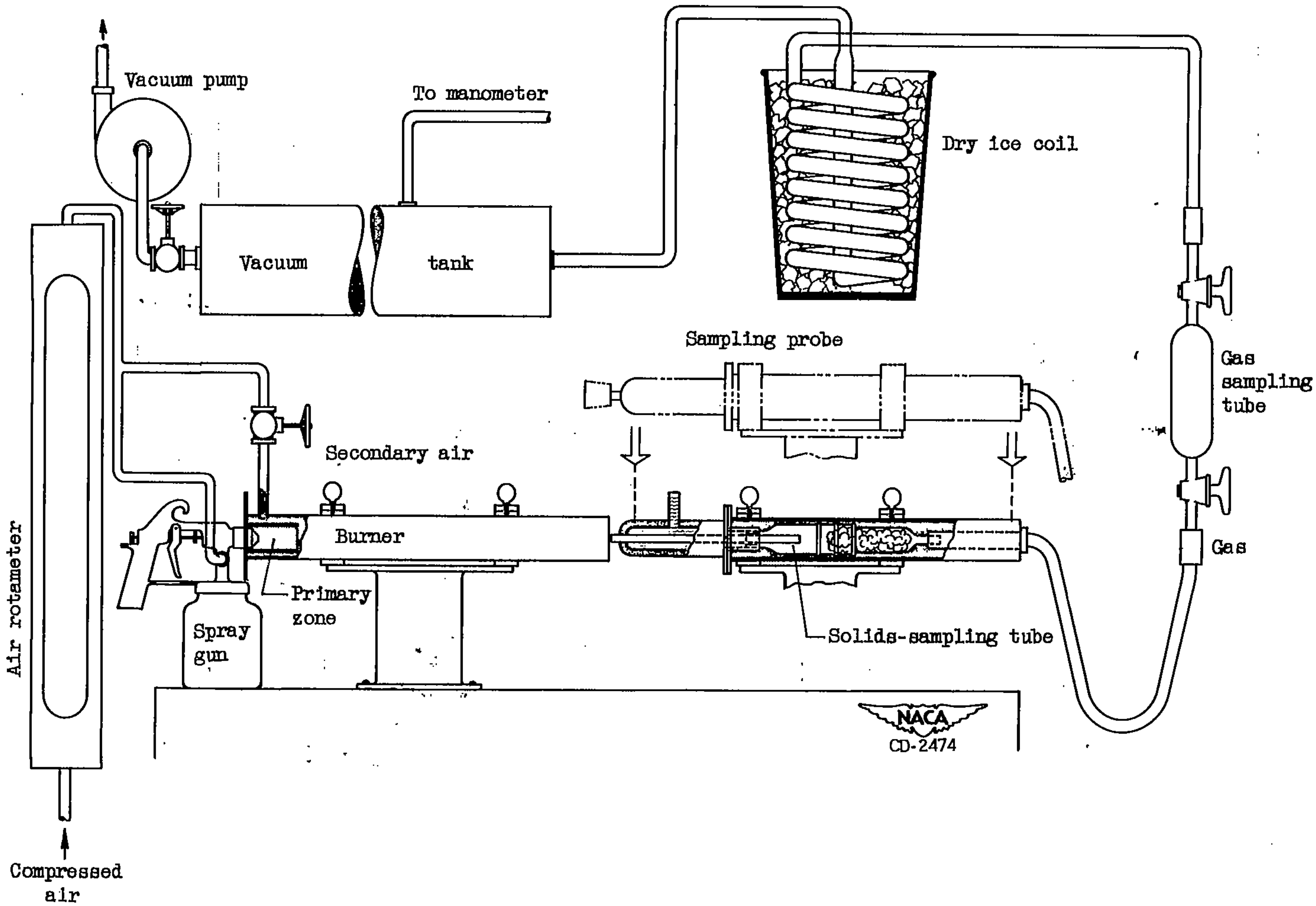

Figure 1. - Slurry burner and sampling apparatus.

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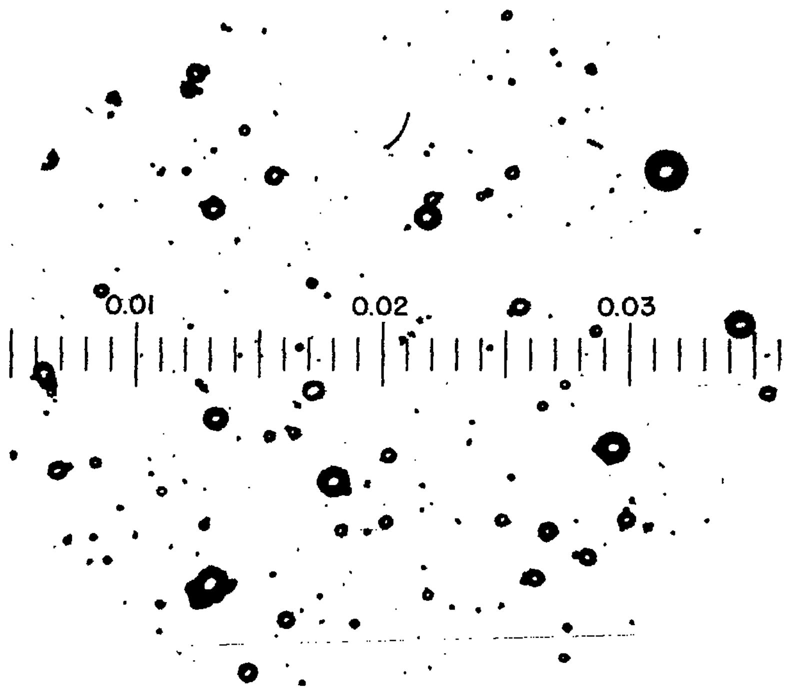

(a) Particle size, 20 microns.

(b) Particle size, 12 microns.

Figure 2. - Photomicrographs of atomized magnesium particles (scale in inches).

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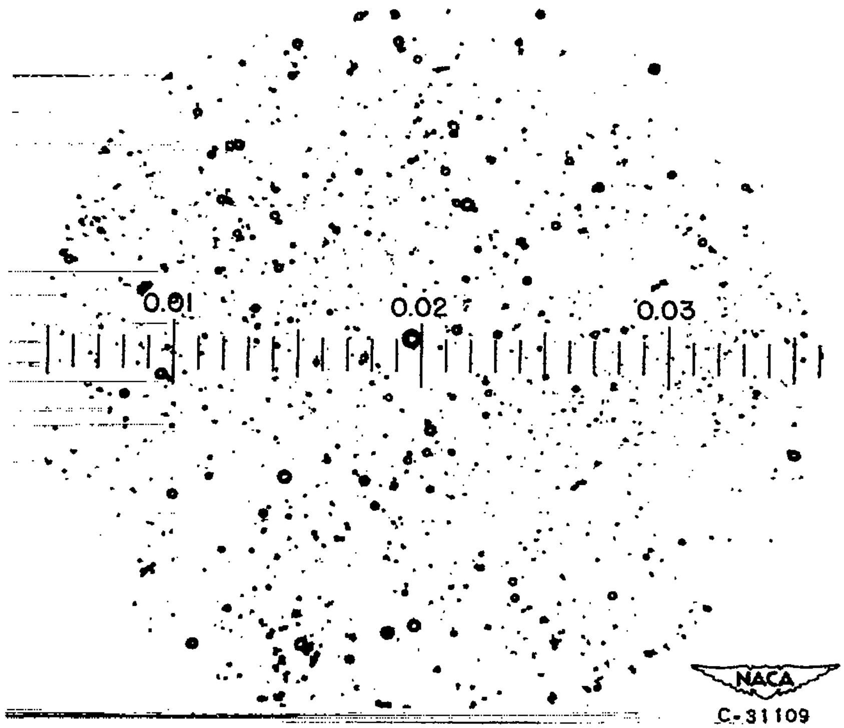

(c) Particle size, $4\frac{1}{2}$ microns.

Figure 2. - Concluded. Photomicrographs of atomized magnesium particles (scale in inches).

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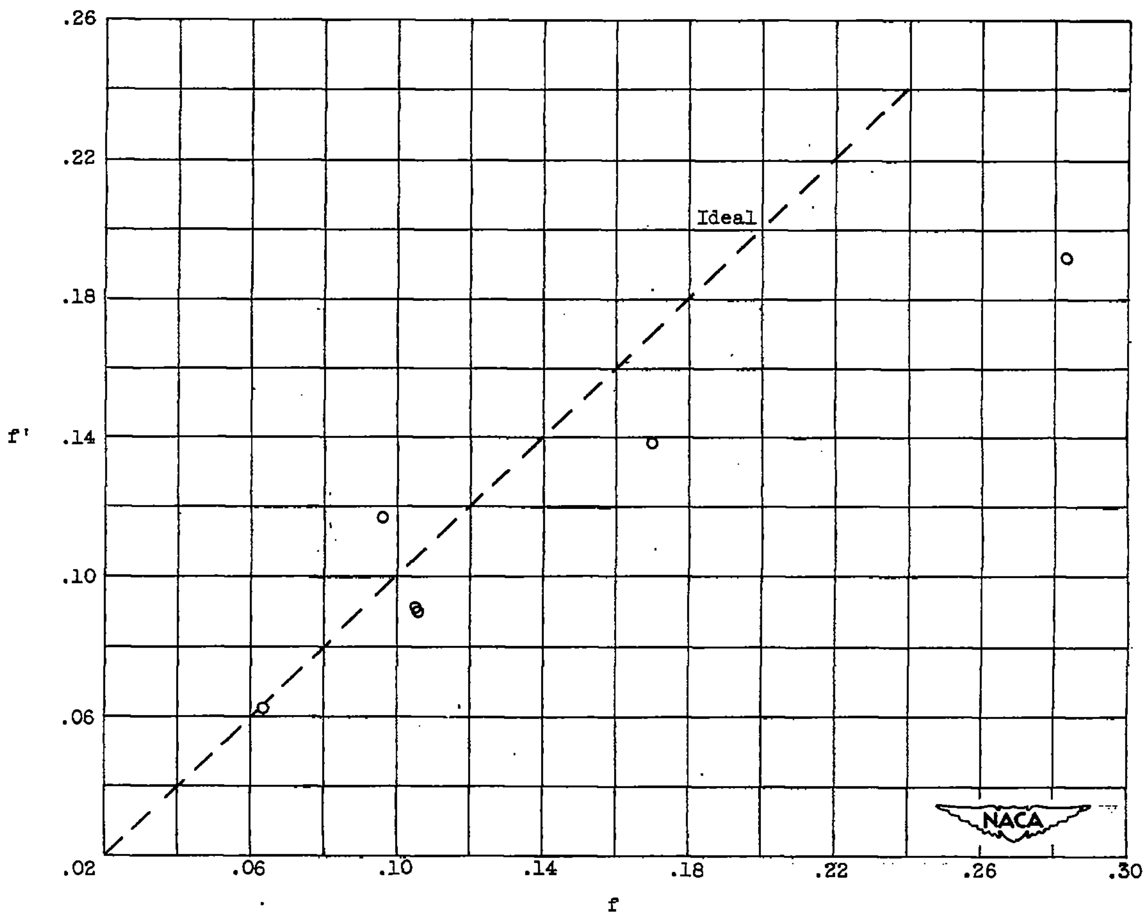
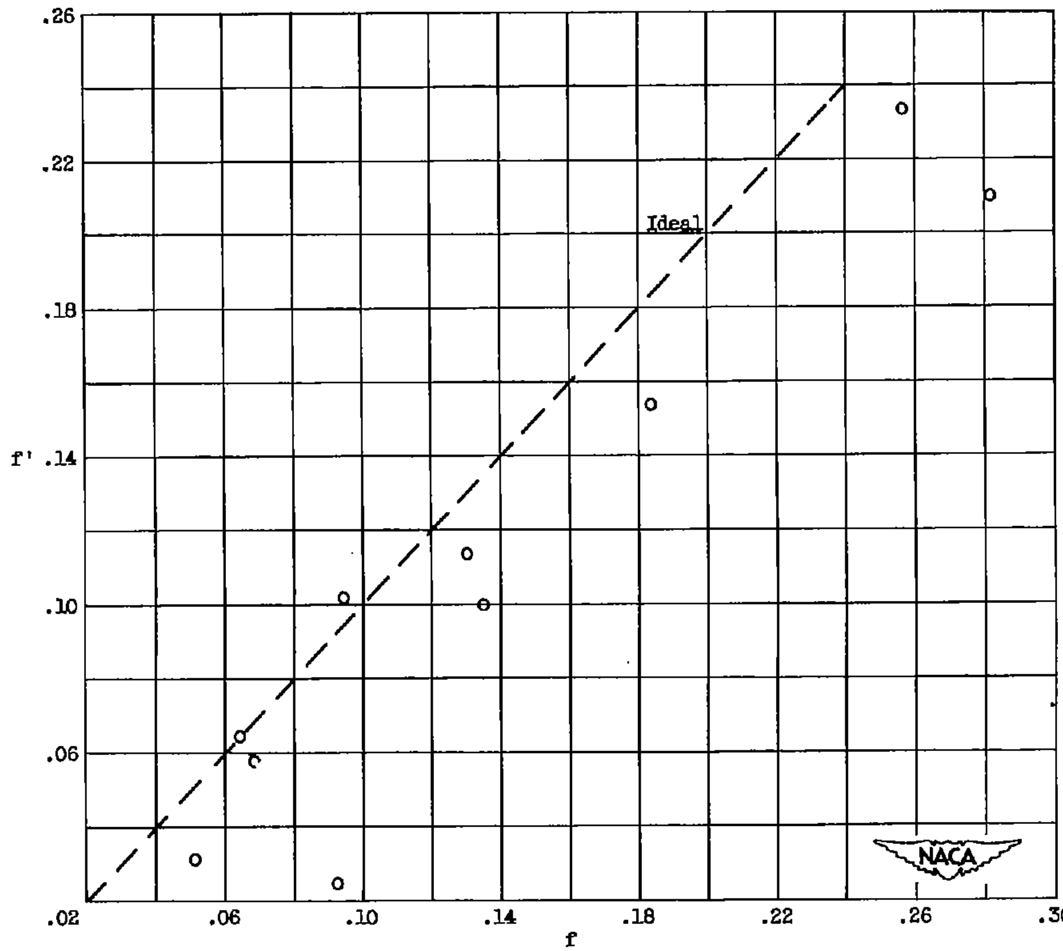


(a) Fuel VI, 50 percent 20-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 21 percent petrolatum.

Figure 3. - Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').



(b) Fuel V, 50 percent 20-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 0.5 percent gelling agent.

Figure 3. - Continued. Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').

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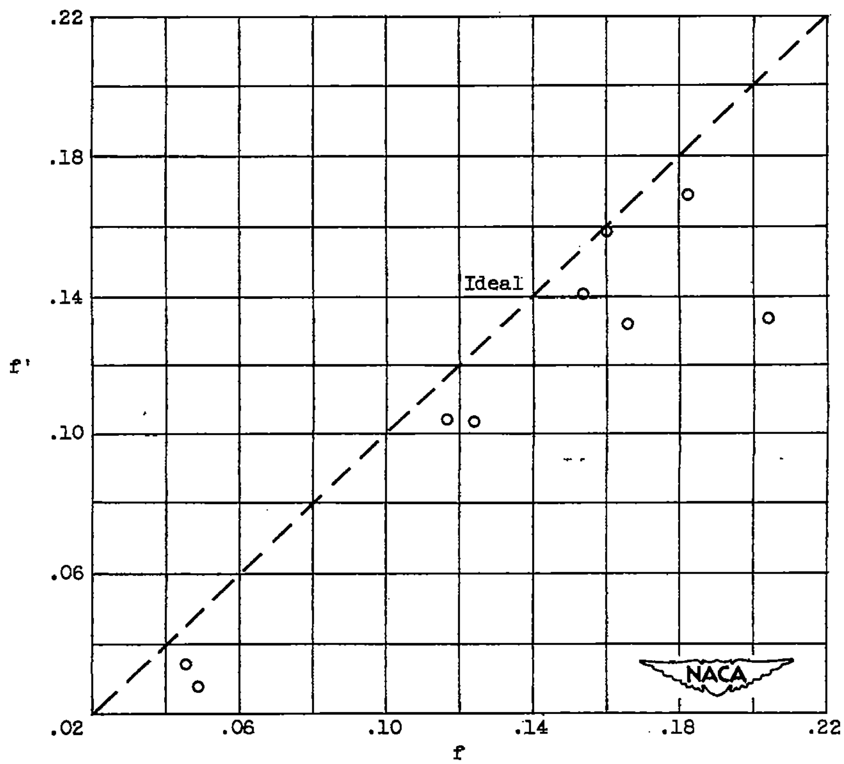

(c) Fuel IX, 50 percent $4\frac{1}{2}$-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 0.6 percent gelling agent.

Figure 3. - Concluded. Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').

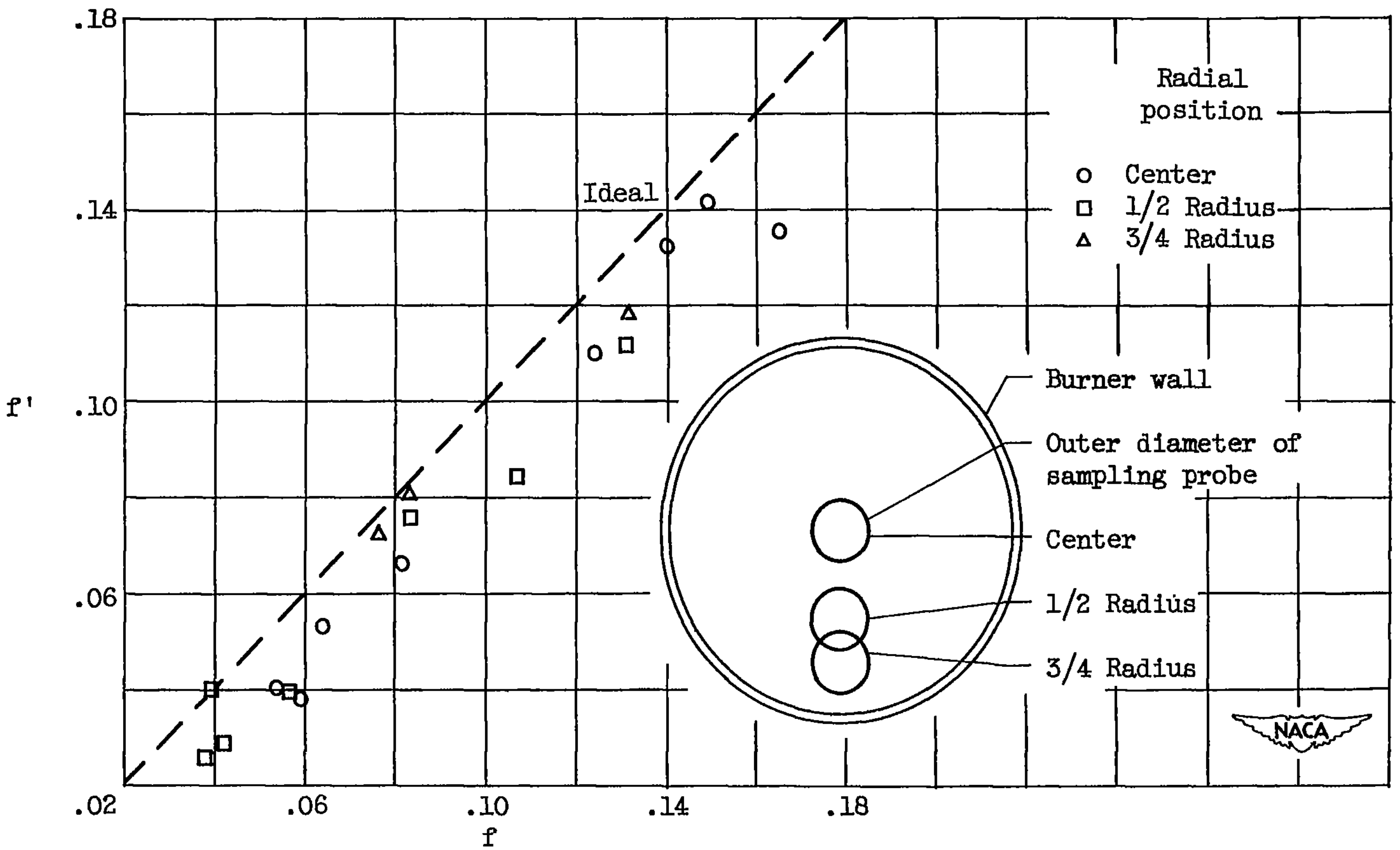

Figure 4. - The effect of sampling probe position on fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f'). Fuel VIII, 50 percent $4\frac{1}{2}$-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 16 percent petrolatum.

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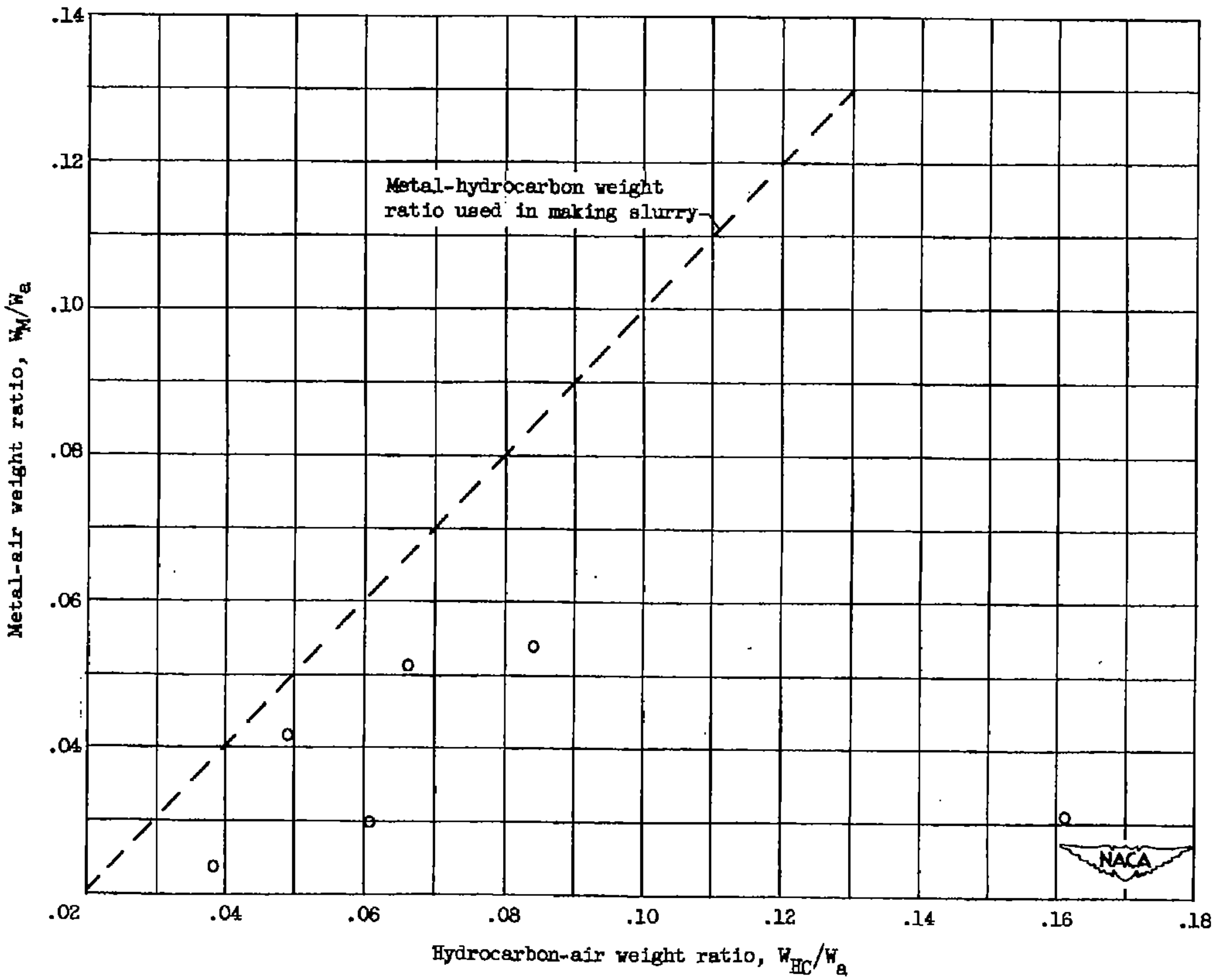
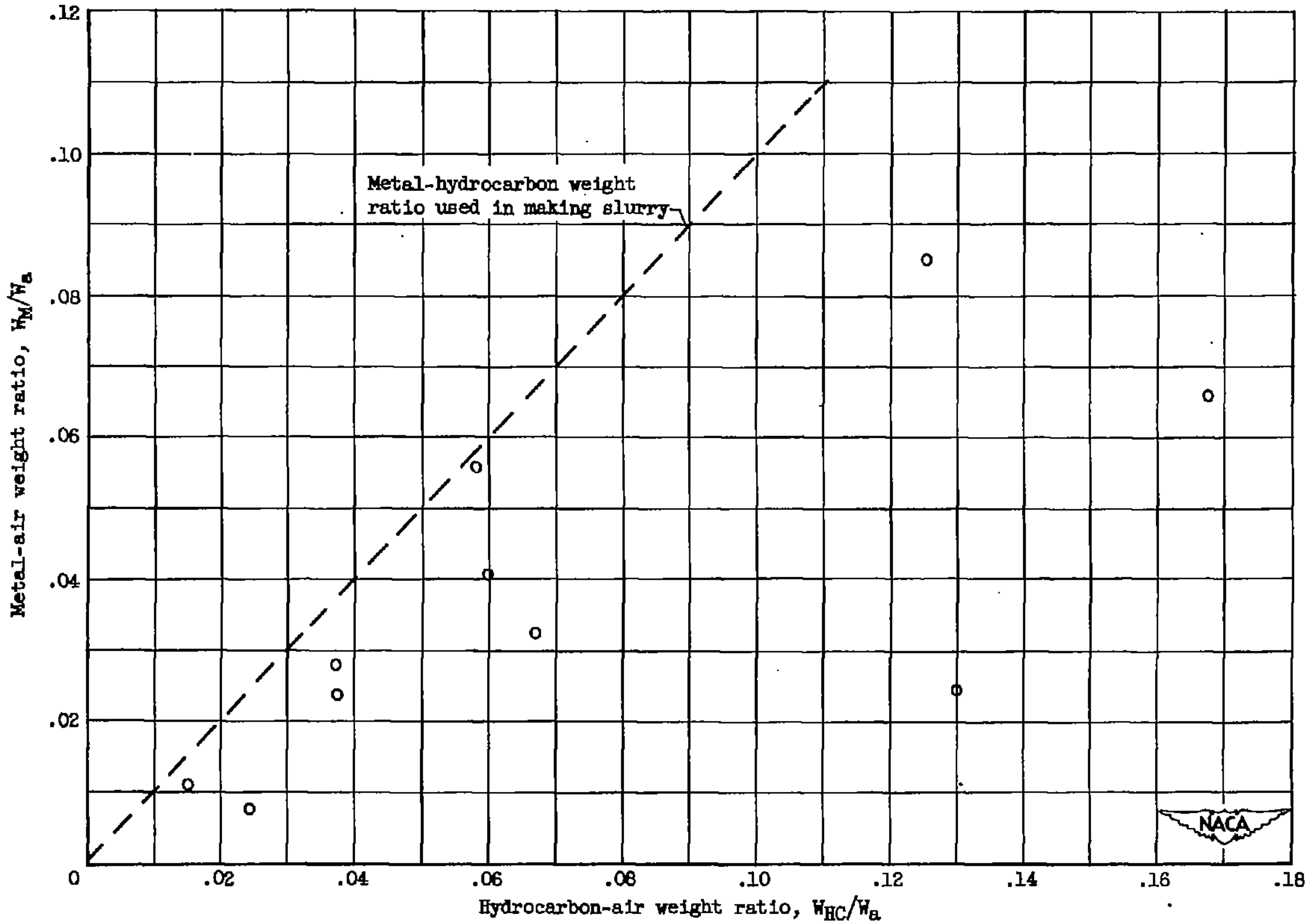


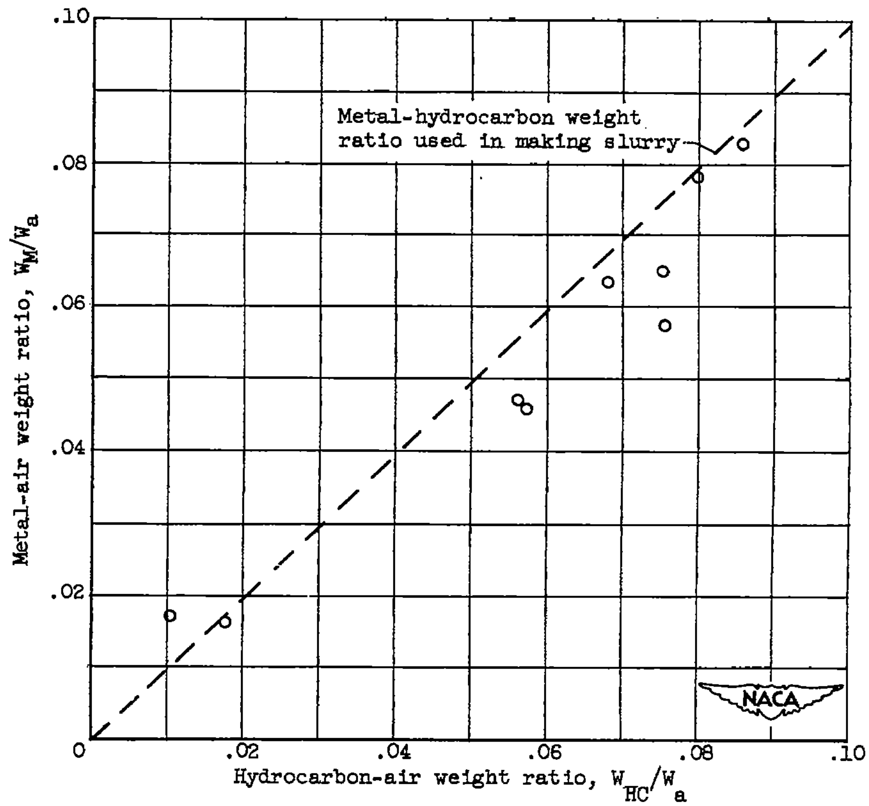
(a) Fuel VI, 50 percent 20-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 21 percent petrolatum.

Figure 5. - Metal-hydrocarbon ratio determined by combustion-products analysis.



(b) Fuel V, 50 percent 20-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 0.5 percent gelling agent.

Figure 5. - Continued. Metal-hydrocarbon ratio determined by combustion-products analysis.



(c) Fuel IX, 50 percent $4\frac{1}{2}$-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 0.6 percent gelling agent.

Figure 5. - Concluded. Metal-hydrocarbon ratio determined by combustion-products analysis.

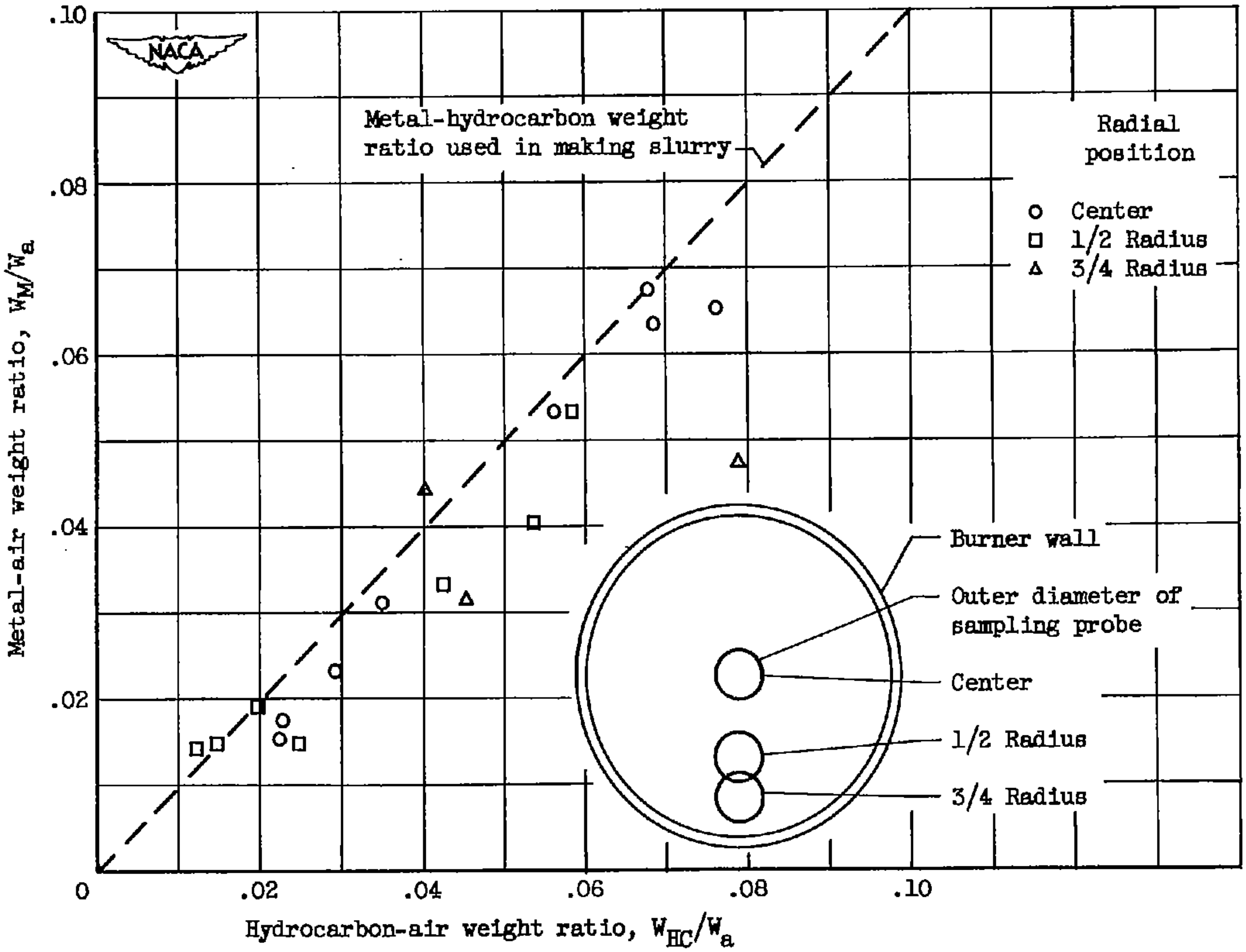


Figure 6. - Effect of sampling-probe position on metal-hydrocarbon ratio determined by combustion-products analysis. Fuel VIII, 50 percent $4\frac{1}{2}$-micron magnesium in MIL-F-5624-A grade JP-3 fuel plus 16 percent petrolatum.

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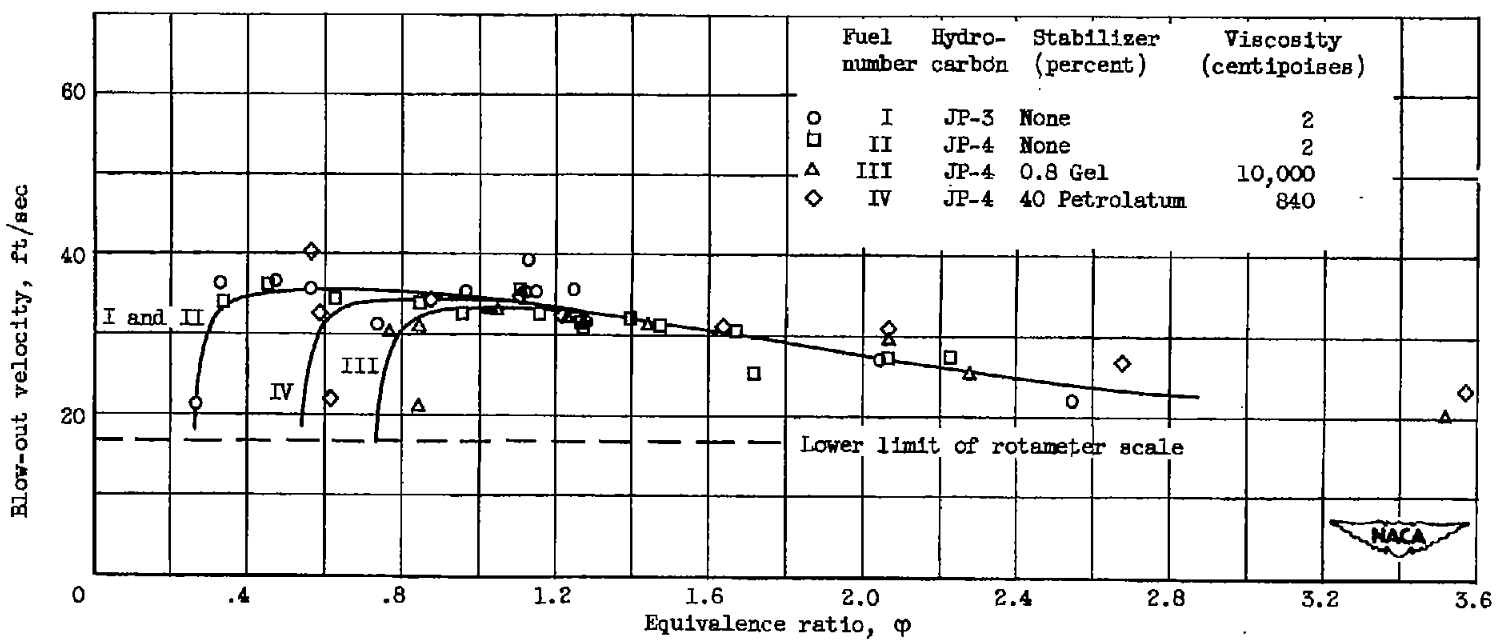

Figure 7. - Comparison of blow-out velocities of JP-3, JP-4, and JP-4 with petrolatum and gel additives.

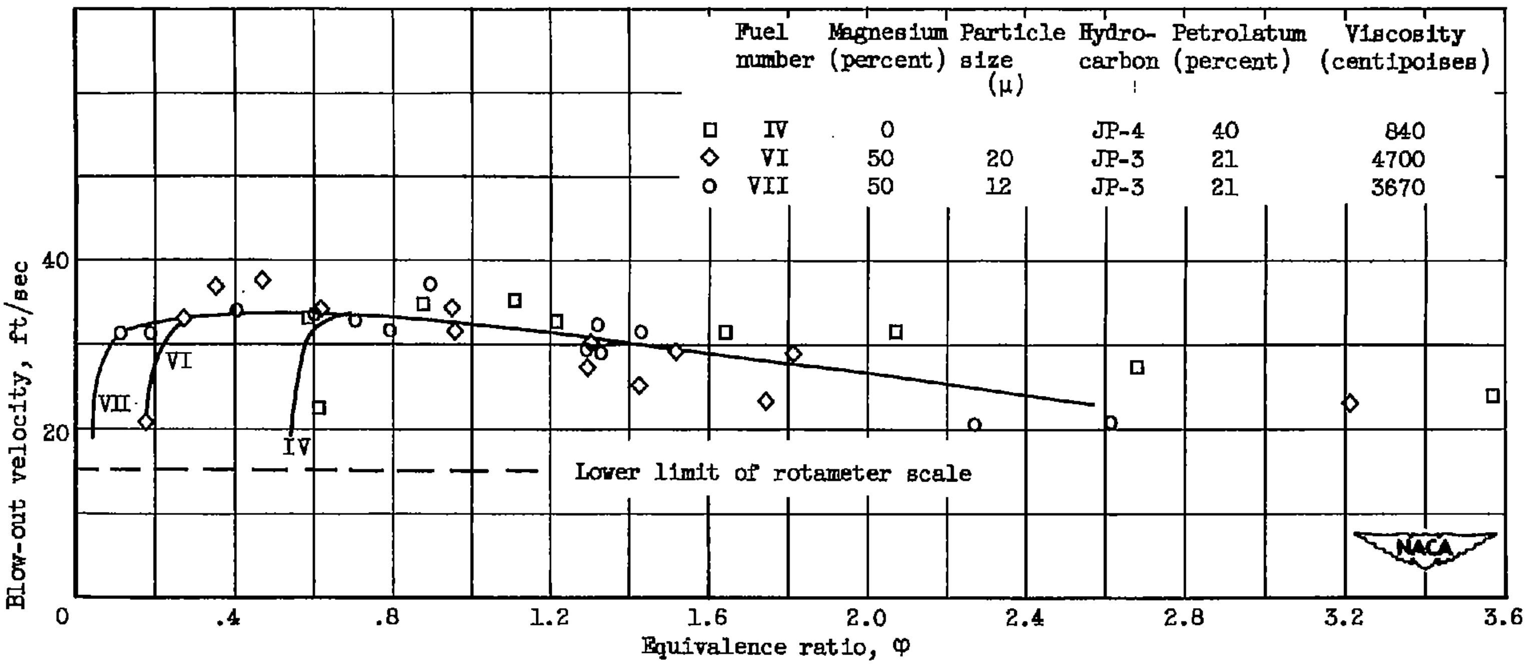

Figure 8. - Comparison of blow-out velocities of 12- and 20-micron magnesium slurries and JP-4 fuel, all with petrolatum additive.

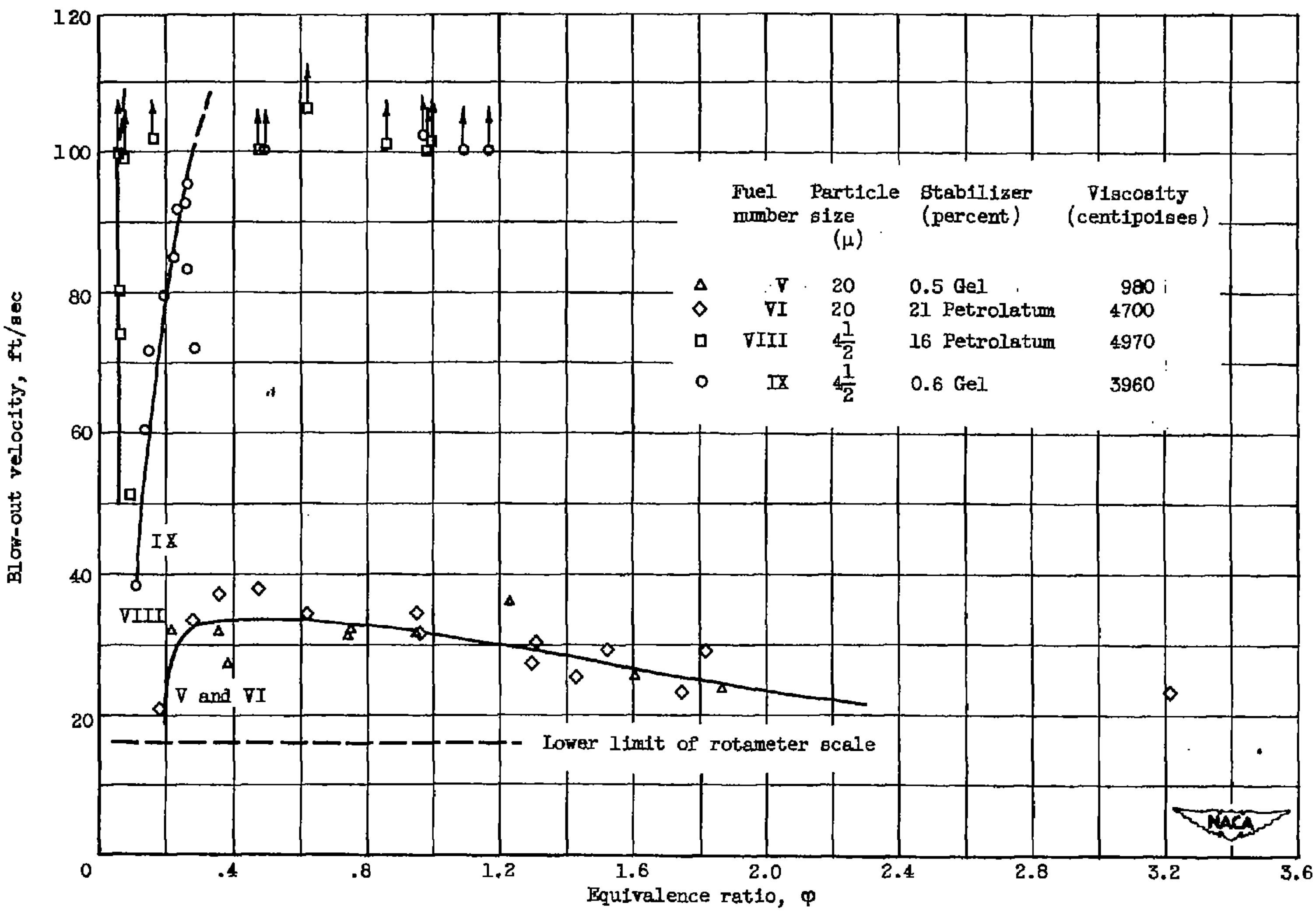

Figure 9. - Comparison of blow-out velocities of $4\frac{1}{2}$- and 20-micron, 50-percent magnesium slurries in JP-3 fuel with petrolatum and gel additives.

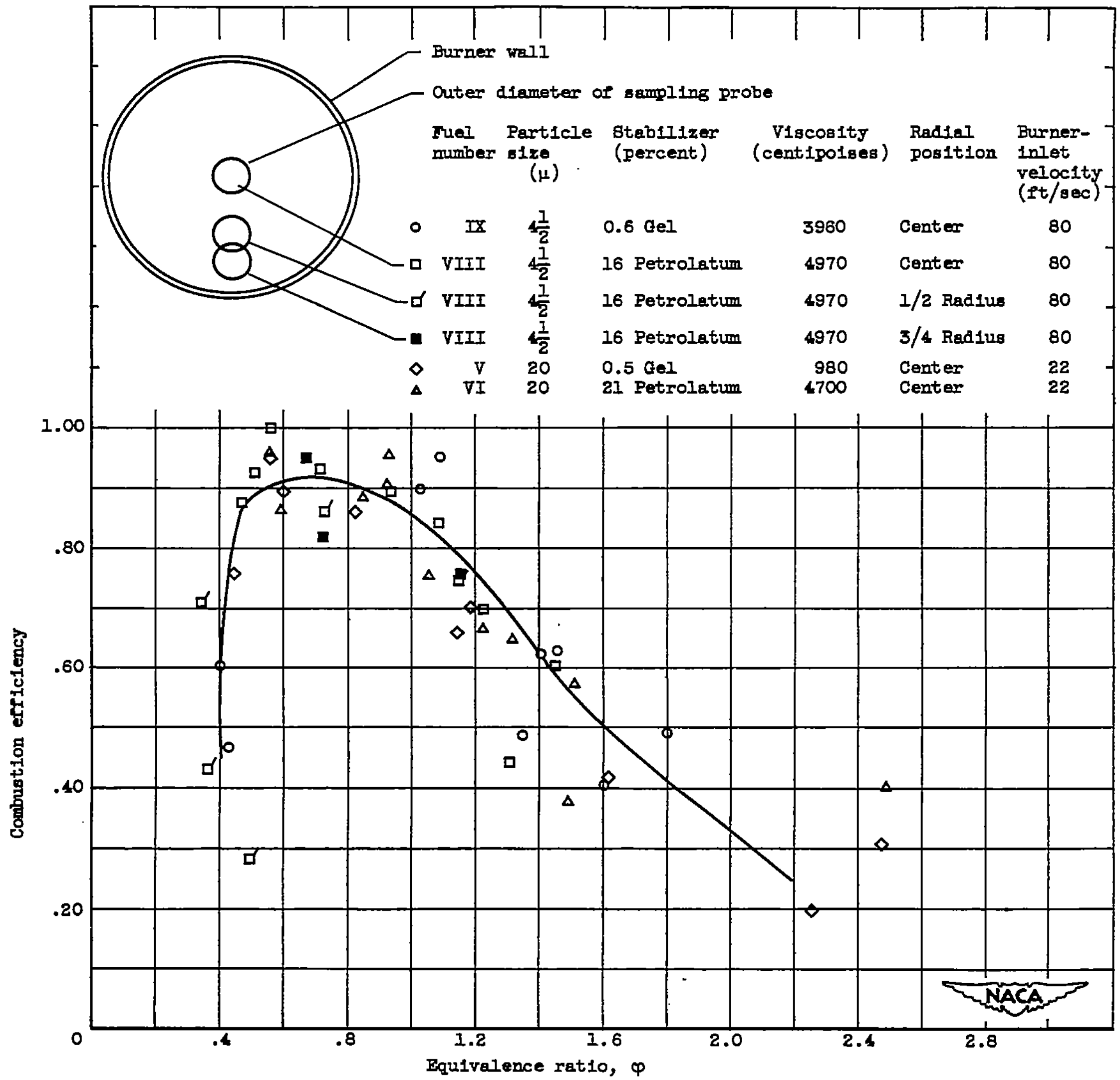

Figure 10. - Effect of equivalence ratio φ on the combustion efficiency of hydrocarbon in 50 percent magnesium, 50 percent JP-3 plus additive, slurry.

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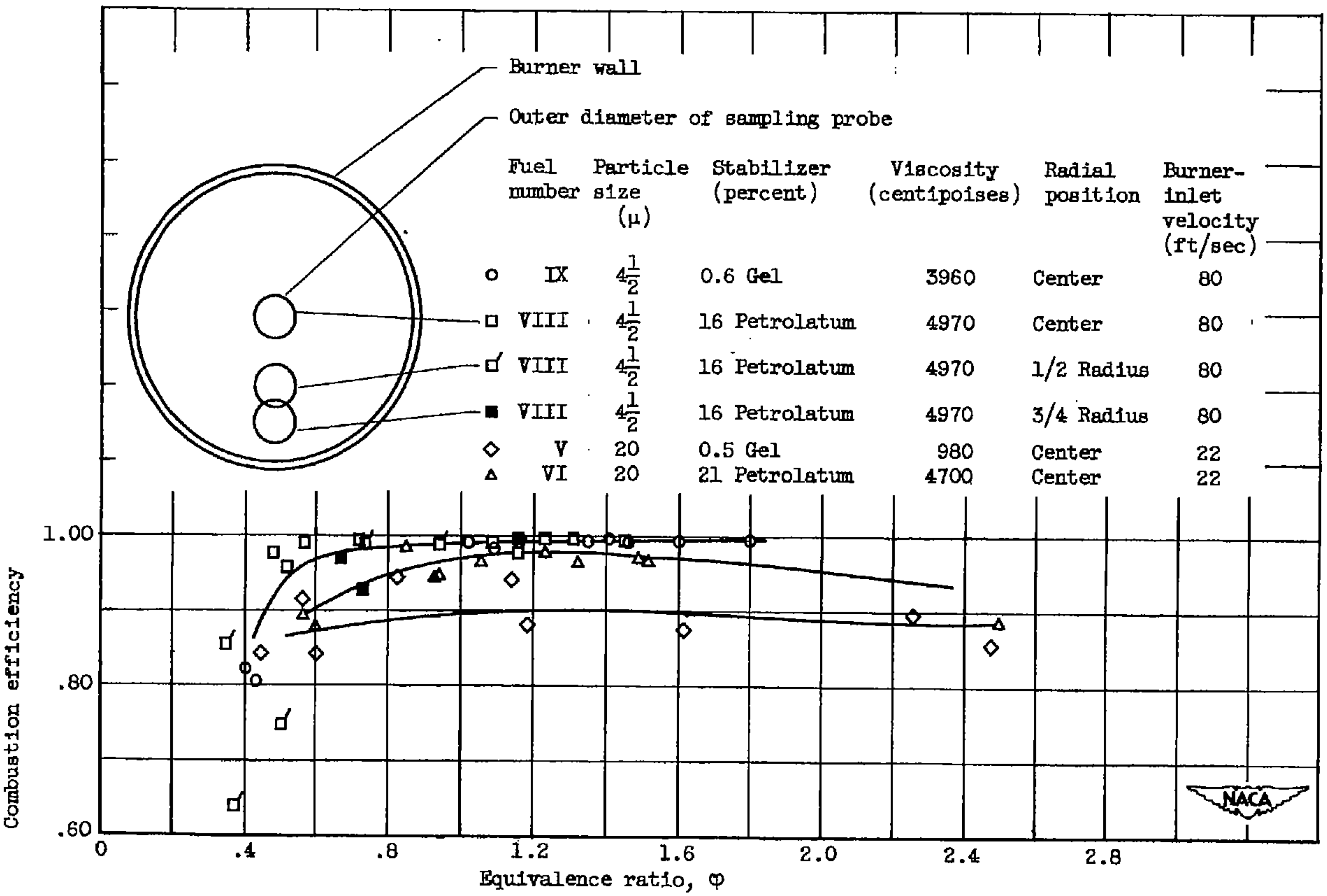

Figure 11. - Effect of equivalence ratio φ on combustion efficiency of metal in 50 percent magnesium, 50 percent JP-3 plus additive, slurry.

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